Received May 9, 2021, accepted May 25, 2021, date of publication June 2, 2021, date of current version June 9, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3085300

A Small Diameter Ultrasonic Water Meter With Self-Diagnosis Function and Self-Adaptive Technology

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This work was supported by the National Natural Science Foundation of China under Grant 11472260.

ABSTRACT Ultrasonic water meters have current widespread problems of poor site adaptability, low measurement accuracy, and poor stability. A high-precision intelligent ultrasonic water meter with self-diagnosis function and adaptive technology was proposed in this paper, which is focus on improving the measurement accuracy and repeatability of the small pipe diameters. The hardware circuit design of the ultrasonic water meter studied in this paper adopts the low-power STM32L053 microcontroller with Cortex-M0 core architecture and the high-precision 11 ps time resolution timing chip TDC-GP30 to complete the metering function. The software combines pulse width ratio and amplitude voltage measurement technology to make the water meter have self-diagnosis function, avoid measurement errors caused by accidental factors, improve adaptability and measurement accuracy, also the application of adaptive measurement period method is used to improve measurement repeatability. The software adopts the moving average filtering algorithm, which effectively reduces the fluctuation of the time-of-flight(ToF) difference and improve the measurement accuracy of the flow point in the low zone (between the minimum flow and the boundary flow). The experimental verification results show that the accuracy of the small-caliber ultrasonic water meter can reach within ± 1.5 %, and the repeatability is less than 0.5 %. In the face of fluid disturbances, adaptive technology is used in this water meter to adjust the measurement period and carry out self-diagnostic function research, and automatically respond to deal with abnormal faults, thereby realizing the demand for intelligence.

INDEX TERMS High-precision intelligent small-diameter ultrasonic water meter, self-diagnosis function, adaptive measurement period, moving average filtering algorithm.

I. INTRODUCTION

The ultrasonic water meter is a new type of electronic water meter based on the measurement principle of the time-of-flight (ToF) difference method [1]. Under the working conditions of the water flow, by detecting the ToF difference caused by the speed change of the ultrasonic sound beam traveling in the water upstream and downstream, it is analyzed and processed to obtain the water velocity to calculate the water flow. And this information is stored and displayed on the electronic instrument [2], [3]. It has excellent small flow detection ability, solves the problems of many traditional mechanical water meters, and is suitable for water resource conservation and rational utilization.

As a high-accuracy flow measurement technique, ultrasonic water meters have been extensively researched in the literature. They have improved the measurement accuracy from measurement methods, optimized filtering, and flow field distribution research. In 2014, French scholar Luca A and others established an ultrasonic flow that can simulate fluids. The metered model provides a basis for analyzing the influence of fluid flow patterns on the flow velocity distribution, and the influence of flow velocity changes on measurement accuracy [4]. In 2015, K. Amri and others used dual ultrasonic transducers. The transducers can transmit and receive each other to measure the ultrasonic wave propagation time.

The associate editor coordinating the review of this manuscript and approving it for publication was Diego Oliva.

The dual ultrasonic transducers are used to improve the anti-interference ability and effectively suppress the influence of sudden changes in flow rate on measurement [5]. In 2019, B. Li and others conducted anti-jamming performance under the complex flow fields research on ultrasonic water meters and proposed ultrasonic signal characteristic analysis, which combines the advantage of the cross-correlation method and the advantage of the threshold comparison method [6]. In 2020, Q. Yu *et al.* proposed a temperature compensation algorithm based on two-dimensional bilinear interpolation in response to the poor environmental adaptability due to temperature effects, which can improve the full flow rate of the ultrasonic water meter and the measurement error at full temperature to be controlled ±2 % [7]. The theoretical results of these scholars have greatly promoted the development of the measurement accuracy of ultrasonic water meters.

However, the environment in which traditional ultrasonic water meters are used in real life is different, and various failures will be encountered during use. The installation position of the ultrasonic water meter in the actual application site is unreasonable and not meet the requirements of the top ten after five rule. there may be disturbance sources downstream of the regulating valve and pump, measurement medium will occasionally have bubbles, the pipe is not full of liquid, by the obstruction or absorption of impurities in the medium, the pipe will be easy to accumulate bubbles, signal strength will be attenuated, which will affect the normal measurement of the ultrasonic water meter. For example, excessive air bubbles and the aging of pipes lead to decreased measurement accuracy, the front-end rectifier filter, and the scale influence may be blocked, resulting in the change of the flow field and affecting the stability [8]. As a result, traditional ultrasonic water meter will face many challenges, which will lead to inaccurate measurement after the failure. Aiming at the failures that may occur during the use of traditional ultrasonic water meters, the research topic of this paper is mainly to have corresponding countermeasures for abnormal failures, and realize the intelligentization of ultrasonic water meters. The key technology lies in the high-precision calculation of the signal stability of ultrasonic propagation and the forward and reverses flow time. Using the new high-precision 11 ps time chip TDC-GP30 [9], combined with the threshold detection technology to calculate the pulse width ratio and the measurement of the amplitude voltage, the ultrasonic water meter has a self-diagnosis function [10] to avoid errors. The adaptive [11] fluid tracking measurement method is adopted to enhance the tracking of the fluid state and automatically adjust the measurement period, thus the water meter can adapt to a more complex environment [13]–[15], also reducing power consumption and improving accuracy. Aiming at the research of high-precision small-diameter ultrasonic water meters, it is necessary to consider the accuracy of small flow in the Low flow point interval. The moving average filter algorithm is added to the digital filter processing of the signal, which effectively reduces the fluctuation of the ToF difference, removes the spikes with large fluctuations, and improves measurement accuracy [16].

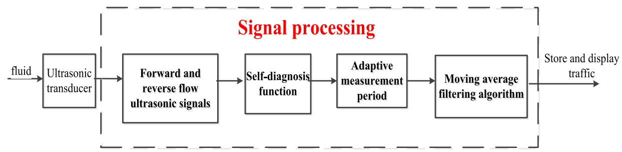

FIGURE 1. The overall design scheme of high-precision ultrasonic intelligent water meter.

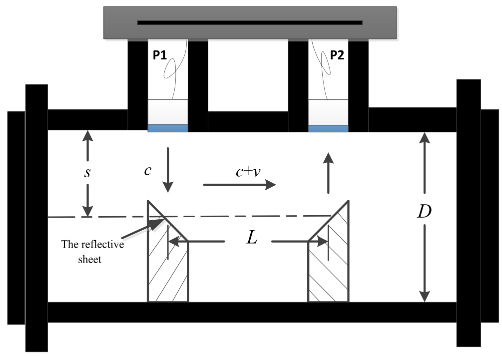

FIGURE 2. U method schematic.

II. OVERALL SYSTEM DESIGN

When there is water flow in the pipeline, the ultrasonic transducer is first excited, so that the ultrasonic signal propagates in the pipeline along the direction of the water flow forward and backward; then get to the signal processing stage, by calculating the ultrasonic signal forward and backward propagation time to obtain the ToF difference signal, the ToF difference signal through the self-diagnosis function module, adaptive measurement period compensation, and then the moving average filter algorithm signal processing, calculate the flow value, finally display and storage the data. Fig. 1 is the overall design scheme of the small pipe diameter ultrasonic intelligent water meter system.

A. PRINCIPLE DIAGRAM OF FLOW MEASUREMENT BY ToF DIFFERENCE METHOD

Household ultrasonic water meter has a small pipe diameter, which is generally between DN15 and DN25. U-shaped reflection measurement method is adopted to eliminate the influence of angle on measurement accuracy, and there is no special requirement for the installation of a transducer, as shown in Fig. 2.

The transducer P1 is a downstream transducer, while P2 is a counter-current transducer. The ultrasonic waves emitted by them are perpendicular to the flow direction. The distance between the transducer and the reflector is s, the ultrasonic velocity in water is c, the angle between the reflector and the horizontal plane is 45°, the center distance between the two reflectors is L, the pipe diameter is D. When P1 emits, and P2 receiving the ultrasonic wave, the time of flight is:

$$t_{12} = \frac{2s}{c} + \frac{L}{c+v} \tag{1}$$

The countercurrent time of receiving ultrasonic waves by P2 and P1 is:

$$t_{21} = \frac{2s}{c} + \frac{L}{c - v} \tag{2}$$

By the (1) and (2), can work out time of flight difference Δt as follows:

$$\Delta t = t_{21} - t_{12} = \frac{2Lv}{c^2 - v^2} \approx \frac{2Lv}{c^2} \tag{3}$$

In (3), because the ultrasonic sound velocity in water is much higher than the fluid velocity, that is $c^2 \gg v^2$, therefore, c^2 in the denominator can be approximately substituted for $c^2 - v^2$. Thus, the linear velocity V_l of water flow can be obtained:

$$v_l = \frac{c^2 \Delta t}{2L} \tag{4}$$

According to the diameter and section size of the fluid pipe, the instantaneous flow can be calculated as:

$$q = Kv_l \frac{\pi D^2}{4} = \frac{K\pi c^2 D^2 \Delta t}{8L} \tag{5}$$

When calculating the instantaneous flow rate and cumulative flow rate, the surface average flow rate is used. According to the relevant knowledge of fluid mechanics, the average surface velocity has different correction coefficients according to the different states of the fluid. In (5), K is the correction coefficient, and the accumulative flow rate Q of the fluid is:

$$Q = \int_0^t q dt = \int_0^t \frac{K\pi c^2 D^2 \Delta t}{8L} dt \tag{6}$$

According to the derivation of the formula given in (6), the water flow is proportional to the time difference between forward and backward flow. Under the condition of the determination of the diameter of the pipe and the distance of the reflector, the flow is only related to the ToF difference and the ultrasonic propagation velocity. Therefore, the measurement of the ToF difference and the ultrasonic sound velocity in the ultrasonic water meter is the key technology.

III. THE HARDWARE DESIGN

This hardware system mainly includes the STM32L053 low power consumption main control chip, TDC-GP30 timing module, power supply module, LCD module, button module, storage module, and infrared communication module. Among them, the TDC-GP30 chip is specifically designed for ultrasonic water meters. The measurement accuracy can reach 11 ps. The circuit is highly integrated. The internal integrated pulse transmitter can emit ultrasonic excitation pulse signals to directly excite the ultrasonic transducer. At the same time, this chip integrates a signal processing module.

IV. SOFTWARE DESIGN

The software system of the ultrasonic water meter is built on the C language development platform of Keil-MDK5, and the main control chip microcontroller is used to call the library functions, divided into different sub-modules, and finally called directly in the main program. First, after the system is powered on, initialize the configuration, select the corresponding communication and working mode, read and erase the data area of the E^2PROM. Then enter the flow measurement program, add the adaptive measurement period function, automatically adjust the timing measurement period according to the fluid state, and notify the main control chip to read the ToF difference and store it in the form of an interrupt at the end of the measurement, and execute the filter algorithm to process the data, and then the main control chip completes the calculation of the flow value, Use the LCD to switch and display cumulative flow information such as instantaneous flow and error recognition.

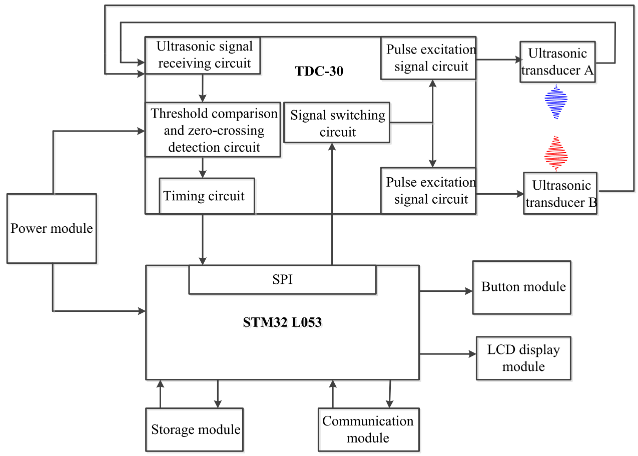

FIGURE 3. Structural design block diagram of the ultrasonic water meter.

A. SELF-DIAGNOSIS FUNCTION RESEARCH

In water measurement, the principle of ToF difference method is used for ultrasonic measurement, but accidental factors and abnormal faults appear in actual measurement, resulting in low measurement accuracy and poor stability. Therefore, a self-diagnosis function and adaptive technology are studied for this situation. The hardware mainly consists of STM32L053 and timing chip TDC-GP30. The software uses a combination of pulse width ratio detection and amplitude voltage to automatically diagnose the on-site adaptability, abnormal fault problems and trigger the corresponding mechanism to deal with. Using the TDC-GP30 as the timing chip, an integrated printed circuit board with self-diagnostic function and adaptive technology is developed as shown in Fig. 4.

First, when the ultrasonic pulse signal is transmitted, it will automatically trigger the timing chip to start the timing start signal, and then the received waveform will be compared with the zero-crossing detection module through the programmable threshold to give the timing stop signal. As shown in Fig. 5, the oscilloscope actually collects the waveform received by the integrated circuit board. The first row is 8 pulse square wave excitation signals with a frequency of 1 MHz and an amplitude of 3.28 V, and the second row is an ultrasonic envelope with a received amplitude of 344 mV. The last line is the converted square wave signal after threshold

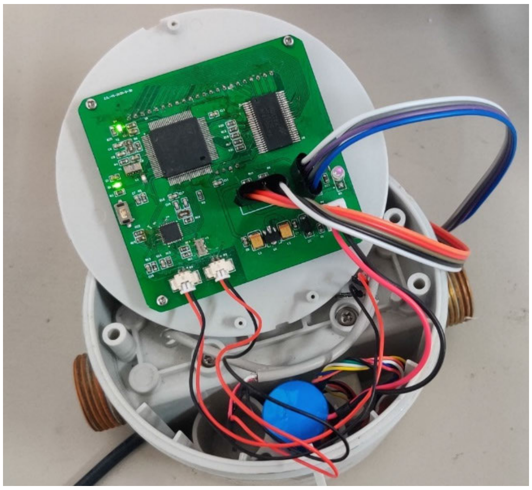

FIGURE 4. **Ultrasonic water meter self-diagnostic function integrated circuit board.**

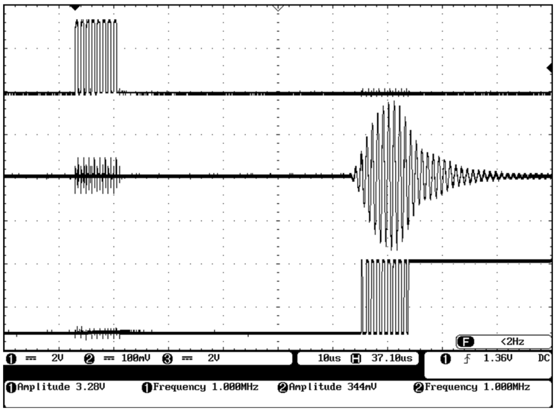

FIGURE 5. **Oscilloscope acquires actual waveform.**

detection and zero-crossing comparison. 8 ultrasonic excitation pulse square wave signals excite the transducer. After a period of time, the ultrasonic envelope signal is received at the receiving end. The threshold value is first compared, and then zero-crossing detection is performed and converted into a square wave. The square wave is sent back to TDC-GP30. The chip calculates and processes.

As shown in Fig. 7, after transmitting the ultrasonic pulse signal for a certain delay time, the ultrasonic envelope signal received in the second row of Fig. 5, the internal comparator of the chip will increase the comparison voltage to the preset threshold voltage, the programmable threshold voltage is set to 35 mV. First, through threshold comparison, low noise and clutter are filtered out to avoid interference with useful ultrasonic signals. When the first ultrasonic envelope signal exceeds the threshold voltage, the chip automatically recognizes this waveform and uses this sampled signal as the first wave signal. The waveforms after the first wave are all ultrasonic echo signals, at the same time, the detection voltage is returned to 0 V for zero crossing detection. The comparison output circuit converts the ultrasonic envelope signal that passes through the threshold and zero point into a square wave signal. After the first wave is sampled, three consecutive sampling pulses are programmed as the timing stop signal, or three sampling pulse intervals can also be set. The number of intervals can be customized. In Fig. 7, the fourth, sixth, and eighth sampling pulse intervals are used as the interval of 1 sampling pulse, the timing stop signal point, and the Fifth, seventh, and ninth sampling pulses are ignored.

As shown in Fig. 8, through the TDC-GP30 internal amplitude voltage measurement module to set, when the ultrasonic signal input is detected, the amplitude voltage measurement starts, the measurement peak can be customized, this article sets the detection of the when the peak is stopped, the TDC-GP30 chip will perform ADC analog-to-digital conversion and store the maximum voltage value measured in this period of time, then the main control chip reads the abnormal fault judgment and processing mechanism.

The TDC-GP30 chip will perform the first wave of sampling. During the sampling process, the TDC-GP30 can perform pulse width ratio detection at the same time. The pulse width ratio coefficient r represents the ratio of the first wave of sampling width to the width of the first timing sampling, and formula can be expressed as:

$$r = \frac{PW\_FH}{PW\_SH} \tag{7}$$

PW_FH is the width of the first wave sampling, the unit is s, PW_SH is the first timing sampling width, the unit is s, and r is a ratio coefficient. The value of r directly reflects the quality of the ultrasonic echo signal. The value of r between (0.6-0.75) indicates that the measurement belongs to the high-quality signal range. As shown in Fig. 6 (a), the pulse width of the collected first wave is reduced, the pulse width ratio r becomes smaller, and the amplitude voltage drops by 1/3. As shown in Fig. 6 (b), the first wave appears when a large number of bubbles or fluid is disturbed. If the wave is detected incorrectly, the second wave is selected as the first wave, which causes the overall technical waveform to extend backward by one period. The wrong counting waveform causes the r to increase. Due to the greater influence of the fluid disturbance amplitude voltage, the voltage amplitude drops by 1/2.

In order to realize the self-diagnosis function research, a simple test bench was built to verify the feasibility of the self-diagnosis function. First, the experimental pipeline adopts PVC transparent pipe, the diameter is DN15, and the transducer is installed at a distance not less than 10 D from the upstream straight pipe.(D is the nominal diameter of the water meter), standard meter of accuracy level 1, pipeline flow regulating valve, water storage tank, and bubble generator are installed.

The experiment uses 2.5 m^3/h as the test point, and the temperature is (25 ± 0.5) °C. Adjust the frequency of the bubble generator to send a different number of bubbles to produce a small number of bubbles and a large number of bubbles when the impact of the two watershed states. Meanwhile

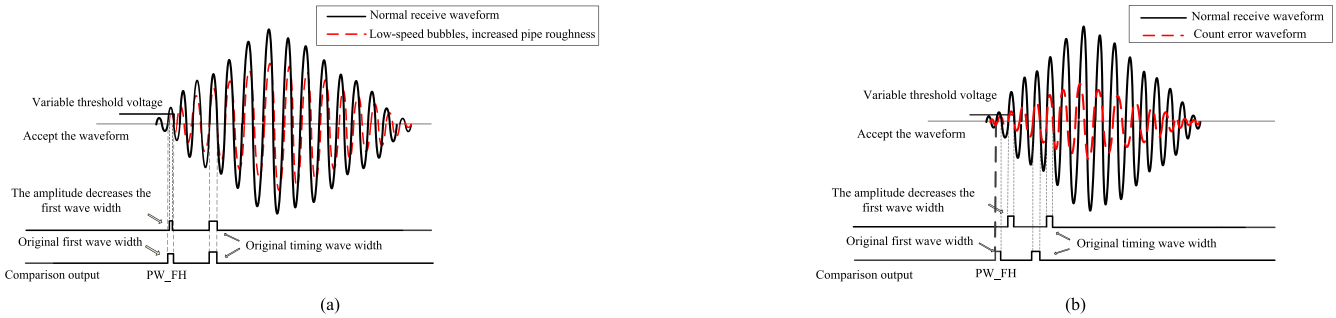

FIGURE 6. **Comparison chart of the abnormal waveform threshold. (a) Pulse width ratio decreases. (b) Counting waveform error.**

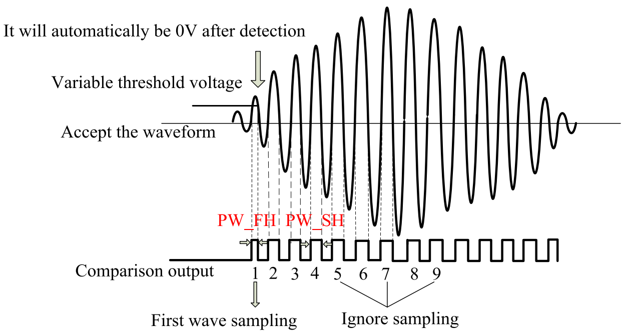

FIGURE 7. **TDC-GP30 internal threshold and zero cross-comparison schematic.**

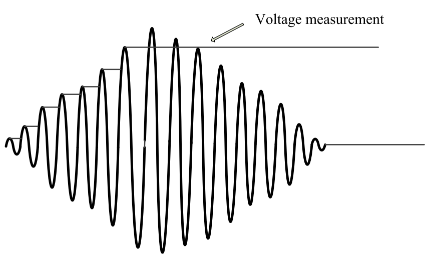

FIGURE 8. **Schematic diagram of amplitude voltage measurement.**

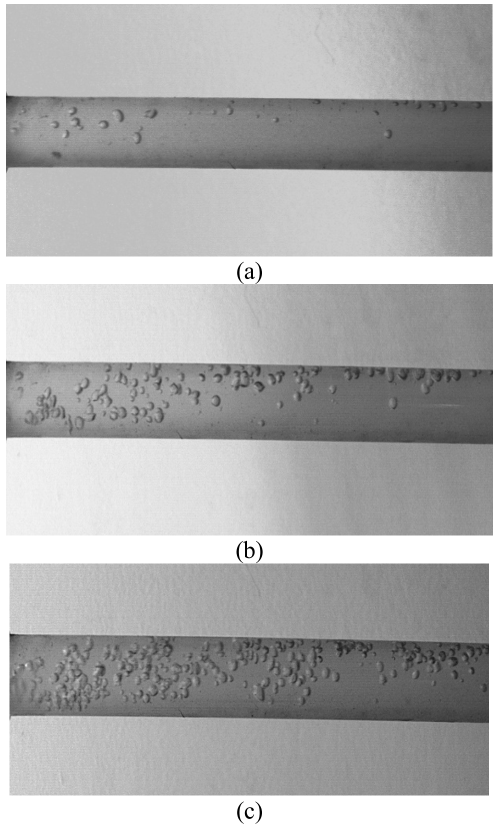

FIGURE 9. **Three watershed state diagrams: (a) a single bubble passing diagram, (b) a continuous few bubbles diagram, (c) a continuous passage of a large number of bubbles diagram.**

a high-speed camera was used to record the occurrence of bubbles, as shown in Fig. 9 (a) below a single bubble passing diagram, Fig. 9 (b) is a continuous few bubbles diagram, Fig. 9 (c) is a continuous passage of a large number of bubbles diagram.

The method of combining pulse width ratio detection and amplitude voltage is used to determine the type of abnormal error and perform self-diagnosis function processing. The purpose is to improve the accuracy and adaptability of the ultrasonic water meter. Pulse width ratio detection is a prerequisite for judging that some abnormal errors occur. First, the ratio of the first wave sampling pulse width to the first timing sampling pulse width is used as the quality detection of the ultrasonic echo signal, and the pulse width ratio (0.6-0.75) is used as the fluctuation range of the high-quality ultrasonic echo signal. Comparing the normal and stable state and the time when a single bubble passes, the error of a single bubble indirectly indicates that the Time_Up(P1 in Fig. 1) or Time_Down(P2 in Fig. 1) time value is equal to 0 s due to the influence of the bubble. At this time, ToF is just a one-way data, and the abnormal data results in an abnormally speed of calculation, which shows a sharp decrease in the pulse width ratio, and self-diagnosis is made according to this situation. The pulse width ratio of 100 sampling points is collected as shown in Fig. 10. The ratio range of the pulse width ratio is used to determine whether an abnormal error has occurred, and then the ADC is used to collect amplitude voltage to read the voltage Compare with the normal amplitude voltage value, if the absolute value difference of the data after comparison is too large, combine the pulse width ratio to judge the type of error.

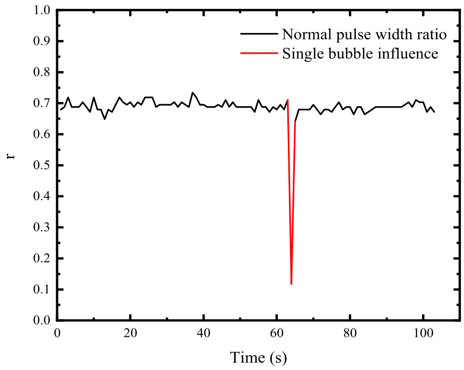

FIGURE 10. **Comparison between normal steady state and a single bubble passing.**

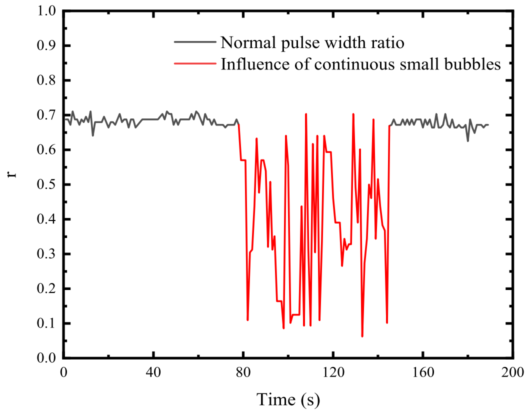

FIGURE 11. **Comparison between normal steady state and When a small number of bubbles pass continuously.**

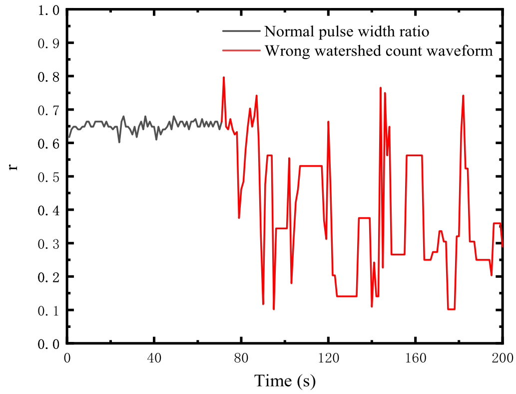

FIGURE 12. **Comparison between normal steady state and incorrect waveform count caused by continuous large number of bubbles.**

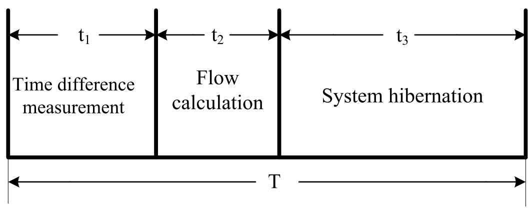

FIGURE 13. **Measurement work sequence in one period of traditional measurement.**

There are two cases to determine the error type. The first is when the r is less than 0.6 and the amplitude voltage is less than one third of the normal voltage range (300-400) mV, it can be judged as a small amount of air bubbles and pipe roughness. The wrong type of accidental factors such as enlargement and dirt on the transducer or reflector will cause the error of the measurement result to become larger. The ultrasonic water meter automatically judges the type and discards these wrong measurement period to deal with the situation when the pulse width ratio decreases. After these accidental factors are eliminated, the normal period measurement can be performed. A small amount of bubbles accidental factors cause the reduction of the pulse width ratio. The data collected at 200 sampling points is shown in Fig. 11.

The second is when the r is greater than 0.75 and the amplitude voltage is less than one-half of the normal voltage range, it can be judged that this type is affected by a large number of bubbles. The ultrasonic water meter automatically increases the measurement period frequency and adaptive flow field changes. A large number of bubbles cause the error of the counting waveform and increase the pulse width ratio. The data of 200 sampling points are collected as shown in Fig. 12.

Ultrasonic water meters use a combination of pulse width ratio detection and amplitude voltage to determine the type of abnormal error and trigger the corresponding self-diagnostic response mechanism. When the influence or error occurs during water metering, it can be found and treated to prevent accidental factors from causing inaccurate measurement and also solve the error influence caused by a large number of bubbles, avoid system errors or accidental factors causing system false alarms, realize stable measurement of ultrasonic water meters, and effectively improve the accuracy and stability of ultrasonic water meters. To reduce the waste of water resources, and make the ultrasonic water meter intelligent.

B. RESEARCH ON ADAPTIVE MEASUREMENT PERIOD METHOD

There are many influencing factors during actual use. Changes in water pressure, air pressure, etc., will cause water flow to fluctuate, fluid disturbances, and instability, which are one of the main factors that cause measurement accuracy decline. The small-diameter ultrasonic water meter is sensitive to the flow state of the basin, using a battery as power and it is impossible to continuously measure and track fluids at high speeds when power consumption is limited. The fluid velocity v of the ultrasonic measurement by the ToF difference method is linearly related to the transit ToF difference Δt. The traditional measurement period is fixed, and the measurement period T is generally set. The measurement work sequence within one period of the traditional measurement is shown in Fig. 13.

In a period, t_1 and t_2 are fixed times, and t_3 changes with the change of the flow measurement period T. The longer the measurement period, the longer the sleep time and the lower

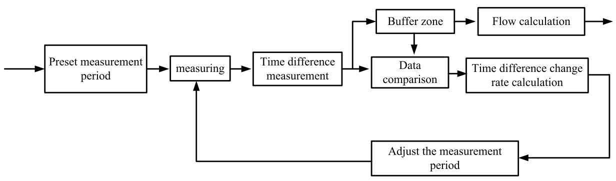

FIGURE 14. Structure diagram of adaptive measurement period method.

the power consumption requirement. Due to the fluctuating nature of the fluid in the pipeline, if the measurement period T is set too small, the measurement accuracy can be improved, but the power consumption will be increased, and the battery life will be reduced; if the measurement period is too long, the measurement accuracy will decrease. Therefore, by analyzing the time measurement period principle and traditional measurement methods in the flow calculation process, an adaptive fast-tracking method with automatic adjustment of the measurement period is proposed [19]. This method is based on the ToF difference change rate and can achieve fast-tracking that changes with fluid changes, it saves power consumption while improving measurement accuracy.

The idea is to increase the measurement period when the rate of change is low, to reduce power consumption, and to reduce the measurement period when the rate of change is high, to improve the fluid tracking ability, and increase the accuracy. Fig. 14 is a structural diagram of an adaptive measurement period method.

The method of adaptive fast-tracking first needs to collect ToF difference samples. Let $(\Delta t)_1, (\Delta t)_2 \ldots (\Delta t)_n$ be n measurement samples, $(\Delta t)_i, (\Delta t)_{i-1}$ are the data of two adjacent ToF difference samples, $(\Delta t)_i$ is the current measurement of ToF difference, $(\Delta t)_{i-1}$ is the last measured ToF difference, T_0 is the initial measurement period of the system, T_{nx} is the next measurement period, that is, the time interval from this measurement to the next measurement, T_{crt} is the period from the last measurement to this measurement. The change rate of the ToF difference between the two measurements is:

$$\varphi_i = \frac{|dt|}{T_{crt}} = \frac{|(\Delta t)_i - (\Delta t)_{i-1}|}{T_{crt}} \tag{8}$$

Among them, dt is the ToF difference change value, φ_i is the ToF difference change rate; let dt_{max} represent the maximum value of the ToF difference change, if the absolute value of the ToF difference between two adjacent measurements is less than dt_{max}, the water meter can continue to measure in this period; if using this, the next ToF difference change rate φ_i predicts the next ToF difference change rate φ_{i+1}, and calculates the next measurement period T_{nx}, then the following relationship must be satisfied:

$$\varphi_i \times T_{nx} \leq |dt_{\max}| \Rightarrow \frac{|(\Delta t)_i - (\Delta t)_{i-1}|}{T_{crt}} \times T_{nx} \leq |dt_{\max}| \tag{9}$$

We can get:

$$T_{nx} \leq \left| \frac{dt_{\max}}{(\Delta t)_i - (\Delta t)_{i-1}} \right| \times T_{crt} \tag{10}$$

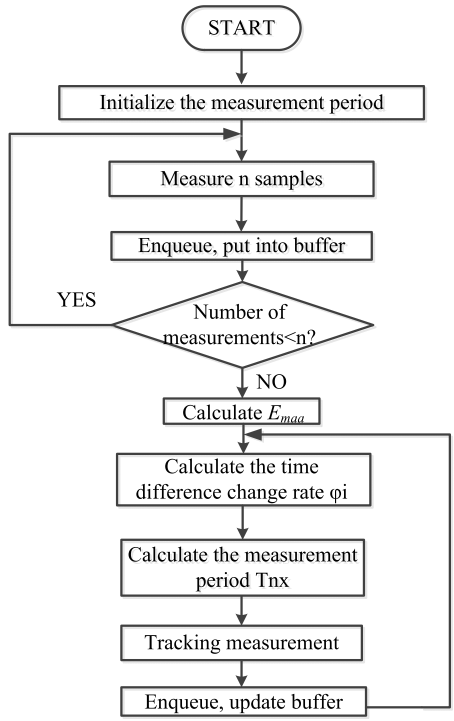

FIGURE 15. Flow chart of the adaptive measurement period method.

Take the largest rapid fluid tracking period in equation (10) as the next measurement period, namely:

$$T_{nx} = \left| \frac{dt_{\max}}{(\Delta t)_i - (\Delta t)_{i-1}} \right| \times T_{crt} \tag{11}$$

Let E_{maa} be the minimum average absolute error of the sample ToF difference, then:

$$E_{maa} = \frac{1}{n} \sum_{j=1}^{n} \left| (\Delta t)_j - \overline{\Delta t} \right| \tag{12}$$

Among them, it is the average value of samples $(\Delta t)_1$, $(\Delta t)_2 \ldots (\Delta t)n$. E_{maa} can reflect the rate of change of the ToF difference. When E_{maa} is smaller, it means that the change of the ToF difference is smaller and the fluid is more stable. When E_{maa} is bigger, it means that the change of the ToF difference is larger and the fluid disturbance is larger. The experiment proves that using E_{maa} instead of dt_{max} can achieve better results. Equation (11) can be transformed into:

$$T_{nx} = \left| \frac{E_{maa}}{(\Delta t)_i - (\Delta t)_{i-1}} \right| \times T_{crt} \tag{13}$$

The specific implementation flowchart of the adaptive measurement period method is shown in Fig. 15:

The above is the steps of the adaptive fluid tracking method. It can be seen that this method has been further optimized on the traditional fluid tracking method, with strong adaptability and fast operation speed, which can effectively improve the accuracy and reduce power consumption.

Fig. 16 is a comparison diagram of adaptive measurement of fluid steady state diagrams. The flow 2.5 m^3/h is used as

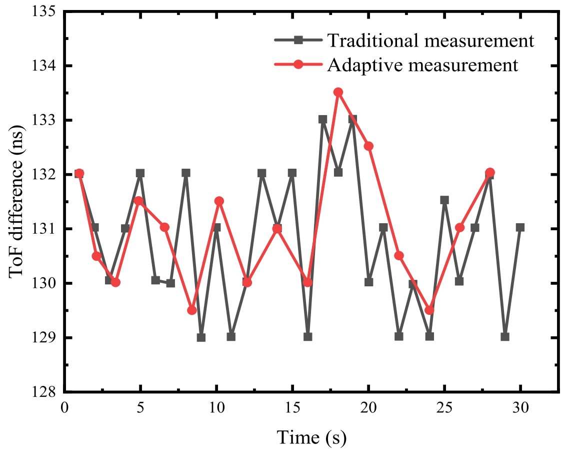

FIGURE 16. Comparison chart of fluid steady-state measurement.

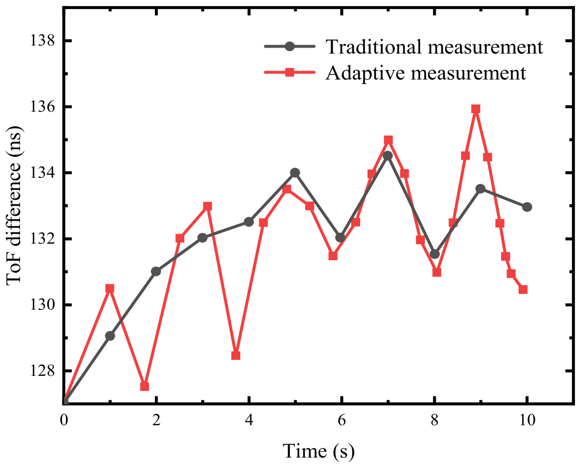

FIGURE 17. Comparison chart of fluid disturbance state measurement.

the test point, the temperature is (25 ± 0.5) °C, the initial measurement period of the two methods is 1s, the buffer length of the adaptive fluid tracking method is set to 48, and the fluid is measured separately under steady-state and disturbance- state, and the two methods are analyzed and compared. Fig. 16 is a broken line diagram of measurement points of the two methods under the stable state of 2.5 m^3/h. The measurement time is set to 30 s. Since the fluid is in a stable state, the adaptive measurement period is 14 times less than the traditional measurement period. The two methods have similar measurement accuracy in the steady-state. The adaptive method reduces the workload of the CPU and reduces power consumption.

Fig. 17 is a comparison diagram of adaptive measurement of fluid disturbance state diagram. By switching the valve in the on-off state, the fluid is in a disturbance state. The measurement time is set to 10 s. The number of measurements in the traditional measurement method is 10 times. Due to the influence of fluid disturbance, the adaptive measurement is superior to the traditional measurement method and has 23 measurements. The ToF difference between the two measurement methods in Fig. 17 is up to 7 ns. Traditional measurement cannot track the state of the fluid, and the measurement process misses the transition of the disturbance situation, which increases the measurement error and leads to the measurement result error.

The advantage of the adaptive technology lies in the automatic tracking of the flow state. When disturbance occurs, the method of reducing the measurement period reduces the occurrence of wrong measurement such as wrong wave, which can reduce the influence of error on repeatability. Wrong wave refers to the measurement cycle frequency is not adapt to the change of the basin, as shown in Fig. 6 (b) the waveform of counting errors, due to the voltage amplitude is reduced, the voltage is less than the threshold value is set, leading to the first stop delay a cycle time, wrong wave phenomenon, using the adaptive adjustment measurement cycle to adapt to changing fluid is a good way to solve the problem of waveform calculation error.

To summarize two points: The adaptive fluid tracking method based on ToF difference can effectively adjust the measurement period according to the ToF difference. Compared with the traditional measurement method, it has two advantages:

1. When the fluid is stable, the ToF difference change rate is low. Under the premise of ensuring accuracy, the ToF difference measurement and fluid flow rate and flow information are measured with a larger measurement period, while reducing power consumption;

2. When the fluid is disturbed, the ToF difference change rate is high, which reduces the measurement period and accurately tracks the fluid change in real-time, improves the measurement accuracy, and avoids the error of the measurement result. Therefore, the adaptive fluid tracking measurement has good measurement characteristics, and it can effectively improve the flow measurement accuracy of ultrasonic water meters in engineering applications.

C. MOVING AVERAGE FILTERING ALGORITHM

Moving average filtering adopts time-domain filtering, which can effectively suppress random noise and keep the steep spike signal [17]. For discrete systems, the moving average filtering algorithm can be regarded as a recursive average filtering algorithm [18]. Take N consecutive sample values as a circular queue, the length of the queue is fixed to N, and each time new data is sampled to the tail of the queue, and one of the original data of the first group is replaced. The data output by the filtering algorithm is always the arithmetic average of the N data in the queue, which has a good suppression effect on the periodic interference of the ToF difference data of the ultrasonic water meter, and the smoothness is high. There is a strong correlation between adjacent data to ensure data smoothness. In the process of designing a small diameter ultrasonic water meter system, there will be deviations between the measurement results and the actual value. The cause of the deviation may come from the quality of the ultrasonic signal, the PCB layout of the circuit board, external electromagnetic interference, etc [20], [21]. And the

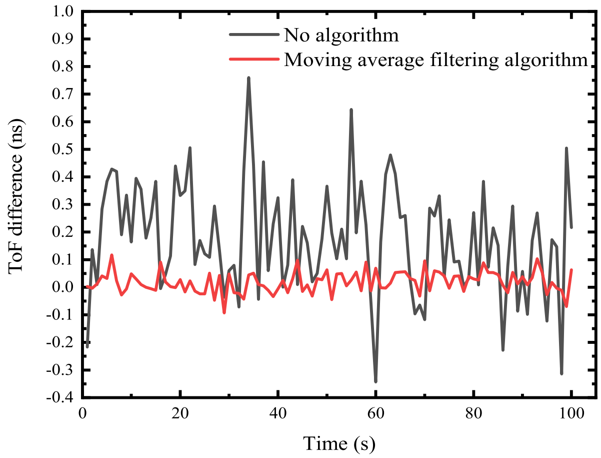

FIGURE 18. Comparison chart of zero drift between no algorithm and moving average filtering algorithm.

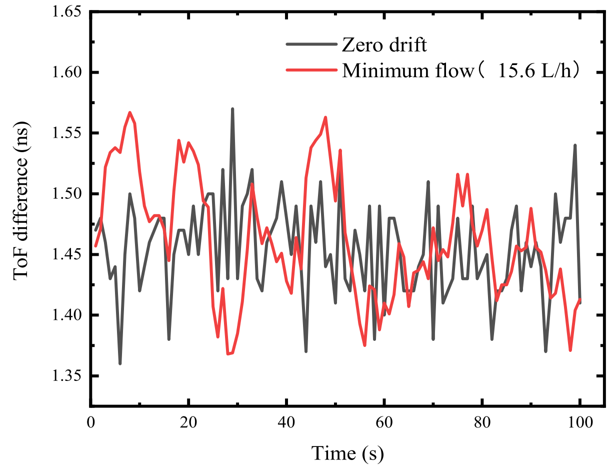

FIGURE 19. Comparison of the ToF difference between zero drift and minimum flow under the moving average filter algorithm.

TABLE 1. Zero drift data analysis.

Symbol	Range(ns)	Standard deviation (ns)
Sample 1	1.014	0.197
Sample 2	0.210	0.038

measurement data must be filtered. Processing to eliminate random errors in the original data, using the moving average data filtering algorithm to ensure the reliability of the data, effectively improve the accuracy of the ultrasonic water meter in the unstable state of the flow, not only reduce the zero drift but also make the flow measurement in a stable state. Zero-drift means that the flow rate is zero under test conditions: the tube segment is filled with liquid. Therefore, the ToF difference data is collected continuously when the flow rate is zero.

In order to compare the effect of data filtering algorithm before and after, 100 sets of the ToF difference data and the original ToF difference data after the moving average filtering algorithm were sampled under standard room temperature and verification environment, and they were marked as sample 1 and sample 2.

Fig. 18 is the data of the zero-drift algorithm of the ultrasonic water meter without algorithm and moving average filtering algorithm collected at temperature (25 ± 0.5) °C. The measured data show that the zero drift range without algorithm is kept within ± 0.55 ns. The zero-drift data obtained after moving average filtering effectively reduces the system zero drift, and the system zero drift range is reduced to within ± 0.10 ns. Compared with no algorithm, the moving average filtering algorithm not only reduces the zero drift by 4/5 but also significantly improves the filtering performance.

By analyzing the standard deviation and range data of the two groups, the range indicates the fluctuation range of the sample data. The smaller the range, the more stable the data, and the smaller the standard deviation, the lower the degree of sample dispersion. From Table 1, the range and standard deviation of sample 2 are the smallest, the data is more stable, and the degree of dispersion is the lowest. It is concluded that the moving average data filtering algorithm can effectively reduce the zero-drift of the ultrasonic water meter, especially to improve the measurement accuracy of the flow point in the low zone.

Fig. 19 is a comparison diagram of the ToF difference between zero drift and minimum flow15.6 L/h of an ultrasonic water meter collected at room temperature under the moving average filtering algorithm. Sample 100 sets of ToF difference data. The ToF difference bandwidth corresponding to zero drift is 0.19 ns and the ToF difference bandwidth under Minimum flow is 0.21 ns. Through the comparison of the ToF difference bandwidth under the zero drift and Minimum flow, it is found that the difference is not significant, with strong stability, and the error fluctuation is small. The corresponding ToF difference calculation under the small flow rate meets the requirements of drip metering accuracy. The advantage of drip metering is that it plays an important role in evaluating the leakage rate of pipeline network and in analyzing and warning the pipeline network.

V. EXPERIMENTAL RESULTS AND DATA ANALYSIS

A. EXPERIMENTAL DEVICE

A prototype of a small diameter ultrasonic water meter with self-diagnosis function and self-adaptive technology, which is mainly composed of integrated transducer pipeline, hardware circuit board, LCD display, large-capacity battery, etc. After the prototype is designed, it is necessary to conduct a flow test on the metering function module, and through data analysis, it is checked and judged whether it meets the design index requirements. Experimental flow test refer to the verification regulation, using volumetric water flow verification device for cumulative flow verification.

Fig. 20 is physical drawing of gas liquid two phase flow experimental platform. The maximum flow rate of the experiment bench is 2.5 m^3/h and the accuracy is 1 %. The device is mainly composed of a water pump, air pump, gas storage

FIGURE 20. Physical drawing of gas liquid two phase flow experimental platform.

tank, water regulator tube, valves of different diameters, standard meter, gas-water mixer, commutator, standard container, pool, and other parts. Install the meter to be inspected, then turn on the water pump and adjust the working frequency of the engine. After the engine is running stably, open the valve and flow for at least 5 minutes, then adjust the valve in the air pump pipeline, intermittent pump a certain amount of air into the water pipeline as a source of interference bubbles, and use the opening of the valve to adjust the number of bubbles. The ordinary ultrasonic water meter without self-diagnosis function and adaptive technology and the new ultrasonic water meter with self-diagnosis function and self-adapting technology are connected in series on the pipeline of the verification equipment. The idea of the control variable method ensures that the two water meters have the same influence on the experimental conditions. Adjust to different flow rates according to the indication of the standard meter. And judge the accuracy of the measurement according to the indication of the tested meter.

B. EXPERIMENTAL DATA

The design index of the high-precision small-diameter ultrasonic water meter is DN15, the range ratio is 160, and the accuracy is within ±1.5 %. In order to verify the diagnosis technology and adaptive technology, choose four flow testing points, which are 100 L/h, 150 L/h, 1000 L/h and 1500 L/h respectively. In the experiment, when measuring at the flow point of 100 L/h, the standard cumulative volume of water measured is 5 L, the volume of water measured at 150 L/h is 10 L, the volume of water measured at 1000 L/h is 50 L, and the volume measured at 1500 L/h is 80 L. Each flow point is verified 3 times. The relative error (14) of water meter verification is:

$$E_{ij} = \frac{Q_{ij} - (Q_s)_{ij}}{(Q_s)_{ij}} \times 100\% \tag{14}$$

E_{ij} is the relative indication error of the water meter during the jth measurement of the ith flow point, Q_{ij} is the cumulative flow of the water meter at the jth measurement of the ith flow point, and $(Qs)_{ij}$ is the cumulative flow of the corresponding standard meter. The experimental data are shown in TABLE 2 and TABLE 3 under (25 ± 0.5) °C.

TABLE 2. Results without self-diagnosis function and self-adaptive technology.

Verification flow point(L/h)	Relative indication error (%)	Average relative error (%)	Repeatability (%)
100	3.44 -0.14 4.28	2.53	2.35
150	-0.36 -2.75 -2.49	-1.87	1.31
1000	1.83 1.10 0.32	1.08	0.75
1500	-0.37 1.54 0.79	0.65	0.96

TABLE 3. Results with self-diagnosis function and self-adaptive technology.

Verification flow point(L/h)	Relative indication error (%)	Average relative error (%)	Repeatability (%)
100	0.38 1.06 0.16	0.53	0.47
150	0.20 0.03 0.84	0.36	0.43
1000	0.93 1.12 1.03	1.02	0.10
1500	0.14 0.28 0.83	0.41	0.37

C. DATA ANALYSIS

This paper studies the unpredictable and unknown errors encountered in the measurement process of ultrasonic water meter. Self-diagnostic function and adaptive technology are used to deal with some interference effects caused by bubbles or impurities in water, so as to avoid the occurrence of error measurement, ensure the repeatability indexes of measurement, and then improve the measurement accuracy of ultrasonic water meter. To our knowledge, there were the first research by using self-diagnosis function and self-adaptive technology after long-term historical exploration of ultrasonic water meters.

Table 2 is the experimental data of the cumulative flow results without self-diagnosis function and self-adaptive technology. the relative average error of the accumulated flow reaches 2.53 %, and the error is too large to difficult measure accurately. Table 3 is the experimental data of the cumulative flow results with self-diagnosis function and self-adaptive technology. It can be seen from Table 3 the

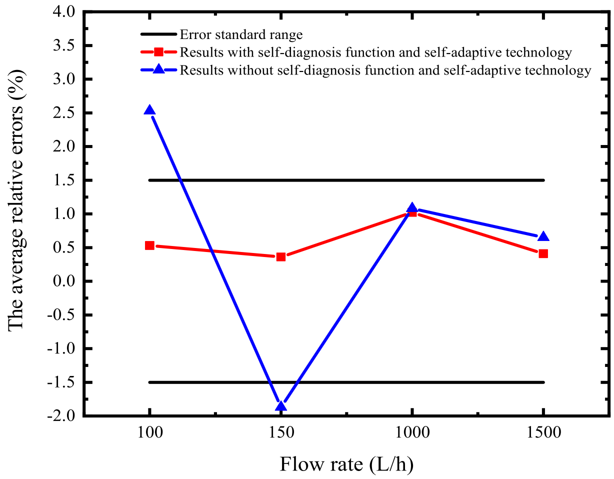

FIGURE 21. **The average relative errors curve.**

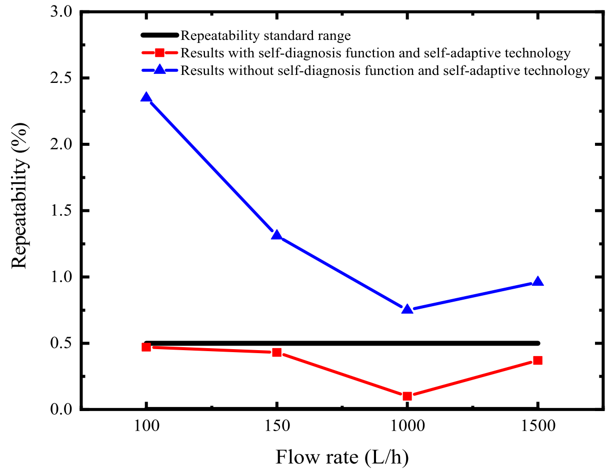

FIGURE 22. **Repeatability curve.**

maximum relative average error of the cumulative flow is reduced to less than 0.6 %. Compared with Table 2, the relative average error has reduced by 60 %, which proves that the self-diagnosis function and adaptive technology relative error is small, and the measurement accuracy is greatly improved.

In order to better compare the superiority of self-diagnosis function and adaptive technology, it is reflected from the repeatability index in Table 2 and Table 3. It can be seen from Table 2 that when the flow point is (1000-1500) L/h, the cumulative flow repeatability is less than 1 %, while the repeatability at (100-150) L/h is as high as 2.35 %, indicating that the random error of the cumulative flow is very large, and the consistency of the indication is very poor. From Table 3, when the flow point is between (100-150) L/h, the cumulative flow repeatability does not exceed 0.5 %, which is significantly better than the repeatability of the cumulative flow in the (100-150) in Table 2. The good repeatability of the instrument ensures the small random error of the measurement of the ultrasonic water meter, indicated that the measurement results have good consistency and stable results, which are the prerequisites for an important measurement index of a high-precision instrument.

Fig. 21 and Fig. 22 are the average relative error and repeatability curves of the cumulative flow. The red curve represents the result with self-diagnosis function and adaptive technology, and the blue curve represents the result without self-diagnosis function and adaptive technology. The black area represents the 1.5 grade standard reference error range.

It can be seen from Fig. 22 that the flow point curve of an ordinary ultrasonic water meter without self-diagnosis function and adaptive technology has poor repeatability of the cumulative flow at (100-1000) L/h, resulting in (100-1000) L/h in Fig. 21 the average relative error of the cumulative flow point did not reach the standard value of ±1.5 %. The repeatability of the cumulative flow does not exceed 0.5 % in the experiment range. The results shown in Fig. 21 correspond to a significant decrease in the mean relative error of the cumulative flow of (100-150)L/h. Compared with ordinary ultrasonic water meters without self-diagnosis and adaptive technology, the repeatability index of which with that is reduced by 80 %, and the accuracy is increased to within ±1.5 %. It is proved that the ultrasonic water meter with self-diagnostic function and adaptive technology can effectively reduce the repeatability of the accumulated flow measurement and thus achieve the requirement of improving the accuracy. Excellent repeatability can guarantee the ultrasonic water meter system's measurement precision and stability, which meets the international standard for the measurement error of the 1.5 grade instruments.

VI. CONCLUSION

In the present study, we investigated the general poor environmental adaptability of small-caliber ultrasonic water meters, the problems of measurement error, low accuracy, and poor stability. A high-precision timing chip with TDC-GP30 as the Measurement core and measurement method based on the principle of ToF difference ultrasonic water meter was proposed, which developed a small diameter Ultrasonic water meter based on the Cortex-M0 core architecture. It has a measure method that combines pulse width ratio detection and amplitude voltage, which can automatically respond and deal with different types of abnormal faults, so that the small diameter ultrasonic water meter has a self-diagnosis function to avoid abnormal data appearance. In response to changes in pipeline flow field and basin, an adaptive period method is proposed to change the measurement frequency to adapt to the change of the flow field and improve the stability of the measurement performance. and it has been verified in experiments. Through the water meter flows laboratory bench, the measurement performance of the ultrasonic water meter prototype was tested, the difficulty of the ultrasonic water meter is that the flow rate in the small pipe diameter is unstable, and it is extremely vulnerable to fluid disturbance, air bubbles, and other accidental factors. Therefore, the self-diagnosis function and adaptive technology are studied to deal with the errors caused by these accidental factors. The software algorithm adds a moving average filter algorithm to reduce the fluctuation of the zero drift and smooth the ToF difference data. In the experiment, the indication error and repeatability requirements with the four flow points is verified, especially the repeatability of in the entire range with less than 0.5 %. The proposed innovation and new technology are verified, and the accuracy and stability of which are tested and analyzed. The accuracy of the ultrasonic water meter can reach within ±1.5 %, which meets the actual engineering needs.

ACKNOWLEDGMENT

The authors express their thanks to the Technical Supporting Staff, Ms. MingYue Yang, Mr. JiaYu Huang, Mr. JianFeng Chen, Mr. Yao Zhao (China Jiliang University) and collaborative partner, Mr. PengFei Zhang (Zhengzhou Tobacco Research Institute of CNTC), and Mr. Jiong Fang (Zhejiang Weixing Intelligent Instrument Company Ltd.).

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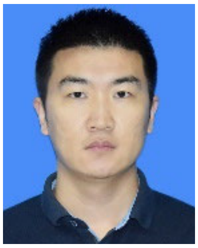

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